"Development of Procurement Guidelines for Air-Cooled Condensers"

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1 Abstract

The use of Air-Cooled Condensers (ACCs) for steam electric power plants has been historically been very limited, especially in the United States. However, with increased focus on water conservation, combined with continued concern over the environmental effects of both once-through and evaporative cooling, the application of ACC's to power plants condenser heat rejection is expected to increase. Indeed, particularly in the Southwestern United States, this has already happened.

As a result of limited operating experience with ACC's and proprietary and evolving dry-cooling technologies, there is no single depository of performance and operations and maintenance experience. Recognizing the increased interest in ACC's and the aforementioned limitations in available data, the Electric Power Research has commissioned Project EPP-P10612/C5386 to develop "procurement guidelines" for ACC's.

This paper presents the results of this work in progress and includes the following areas:

A. An assessment of operating and performance issues with ACC's,
B. The development of information that should be included in and solicited via procurement specifications for ACC's,
C. An example procedures for evaluation and comparisons of bids, and
D. Guidelines for Performance and Acceptance Testing of ACC's.

Particular emphasis is placed on observations of the effects of winds on the performance of ACC's. Recommendations for language which might be incorporated into procurement specifications, in this regard, are also included. Finally, a summary of a proposed test guideline for ACC's is included as Codes for these tests are under development by both the American Society of Mechanical Engineers and the Cooling Technology Institute, and are not expected to be published in the foreseeable future.

2 Introduction

2.1 EPRI Project Overview

With increased focus on water conservation, combined with continued concern over the environmental effects of both once-through and evaporative cooling, the application of ACC's to power plants condenser heat rejection is expected to increase. Evidence of this trend is apparent in the Southwestern United States, where population growth and development initiatives solicit increased power generation, while competing for limited supplies of water.

As a result of limited operating experience with ACC's and proprietary and evolving dry-cooling technologies, there is no single depository of performance and operations and maintenance experience. Recognizing the increased interest in ACC's and the aforementioned limitations in available data, the Electric Power Research has commissioned Project EPP-P10612/C5386 to develop "procurement guidelines" for ACC's. This paper summarizes some of the key products of that project.

2.2 Site Assessments and Potential Areas of Focus

Numerous specifications, technical papers and books **[1,2]**, have been developed for ACC's both internationally and in the United States. The specifications, for the most part, cover the design conditions, scope of supply, codes and standards, contract terms and conditions, etc. In most cases, these specifications have not addressed areas that might be problematic, in terms of ACC performance, operation and maintenance. In developing information that was felt important to ACC specifications, a number of sites were visited as part of the specification development process. Interviews with both plant personnel and suppliers were conducted, in order to gain a balanced viewpoint on key issues. The following areas surfaced as ones which deserved additional attention, beyond the historical level that they have received:

2.2.1 Wind Effects

Prevailing winds can be significant at many sites, especially given the typical height of air inlets and fans (e.g. 50-100ft (15-30 m)) on an ACC. High winds can cause reduced inlet pressures on upwind fans of an ACC leading to reduced airflow rates and cell thermal performance. Prevailing winds can also lead to recirculation of the heated exhaust air from the ACC, also leading to reduced performance of the ACC. This area, i.e. wind effects (which includes issues such as fan performance impacts, recirculation effects, tube bundle exhaust air flow, and interference), represents a major challenge associated with ACC specification, design and performance.

2.2.2 Range of Operating Conditions

ACC's may be required to operate over ambient temperatures ranging from less than 0°F to over 110 °F. Further, they may also be required to undergo "cold starts" (i.e. initial operation without a heat load) and operate successfully over a full range of heat loads. In doing so, particular attention in the design and operation of the ACC to prevent freezing of condensate as well as proper removal of non-condensables is critical.

2.2.3 Fouling of ACC Coils

Many ACC's operate in areas with high ambient dust loadings. This is particularly true in the desert Southwest portion of the U.S., where a number of ACC's have recently been commissioned. In some situations, beyond ambient dusts, pollen, insects, etc. can foul heat exchange surfaces. Further, leaky gear boxes lead to carryover of gear box grease to the heat exchange surfaces. It may also be the case that nearby fuel piles, including coal, hog fuel (i.e. wood waste) etc. can contribute to the inlet air dust loadings to the ACC and resultant fouling. As a result of site visits, incorporation of potential dust loadings, fin-tube cleaning systems and performance degradation trends warrant additional consideration.

2.2.4 Inlet Air Conditioning

A number of ACC Owner/Operators have experimented with and/or are using methods for inlet air cooling of the ACC. The notion of reducing the inlet air dry-bulb temperature, particularly during periods of elevated temperatures is obviously important when power output requirements are highest. Inlet air cooling typically involves evaporative cooling of the air via either film or spray cooling. In the case of film cooling, additional pressure drop on the inlet air side can be a challenge. In the case of spray cooling, carry over of sprayed droplets can also be problematic. Indeed, spray cooling via atomized sprays, has resulted in degradation of finned tube surfaces at a number of sites. The main reason for this is felt to be improper selection, positioning and/or orientation of atomizing technologies. Accordingly, one should not write off the prospect for inlet air cooling via sprays.

3 ACC Specification Development

3.1 Development of Design Conditions

The *minimum* amount of information required to establish the simplest design point for an ACC is:

- Steam flow, W (lb/hr)
- Turbine exhaust team quality, x (lb dry steam/lb turbine exhaust flow)
- Turbine backpressure, p_b (in Hga)
- Ambient temperature, T_{amb} (deg F)
- Site elevation, (ft---above sea level)

"Steam flow" refers to the total flow passing through the steam turbine exhaust flange and consists of both dry steam and entrained liquid water droplets.

"Steam quality" refers to the fraction of the steam flow which is dry steam and is expressed as a decimal fraction or a percent. All dry steam at saturation conditions has a quality of 100% (x = 1.). An equivalent description sometimes used is "steam moisture" (ξ) defined as the percent of liquid water in the "steam flow". Therefore,

$$\boldsymbol{\xi = 1. - x} \qquad \{1\}$$

These quantities are used, along with the thermodynamic properties of steam and water including the latent heat of vaporization, h_{fg} (Btu/lb), at the design condensing pressure, to determine the heat load, Q (Btu/hr), which must be handled by the ACC. Since the heat load is determined by the total steam flow times the difference between the enthalpy of the inlet steam, $h_{steam\ inlet}$ (Btu/lb) and the enthalpy of the leaving condensate, h_{cond} (Btu/lb), it can be shown that

$$\mathbf{Q(Btu/hr) = W(lb/hr) * x(lb/lb) * h_{fg}(Btu/lb)} \qquad \{2\}$$

The turbine steam flow and quality at the plant design load are obtained from information provided by the turbine vendor.

In addition to these basic quantities, the ACC design (and cost) may be affected by a number of plant and site characteristics which are listed below.

- Site characteristics
    - Meteorology
        - Annual temperature duration curves
        - Prevailing wind speeds and directions
        - Extreme conditions (hottest day; freezing conditions)
- Topography and obstructions
    - Nearby hills, valleys, etc.
    - Nearby structures, coal piles, etc.

        - Nearby heat sources---aux. coolers, plant vents, etc.
- Other
    - Noise limitations
        - At ACC
        - At some specified distance---neighbors, sanctuaries, etc.
    - Maximum height restrictions
    - “Footprint” constraints (length, width)
    - Location restrictions---distance from turbine exhaust

3.2 Basic Design Determination

Specification of the quantities and characteristics above are sufficient to obtain a “budget” estimate from ACC vendors. The following example illustrates the considerations in selecting an appropriate design point.

An ACC for installation at a 500 MW (nominal), gas-fired combined-cycle plant located in an arid, desert region might select the following design values:

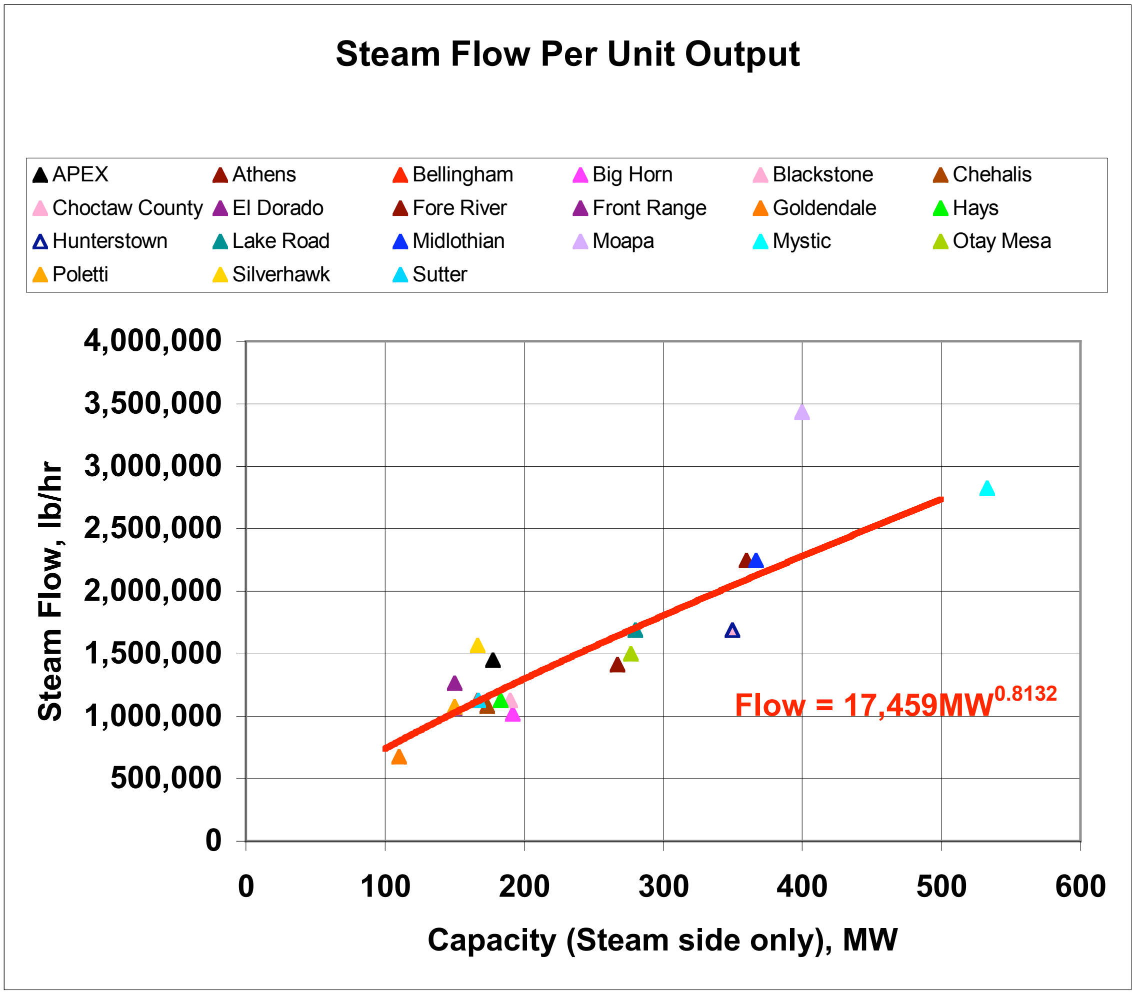
• Steam flow, W (lb/hr):	1.1×10^6
• Quality, x (lb/lb)	0.95
• Backpressure, p_b (in Hga)	4.0
• Ambient temperature, T_{amb} (F)	80
• Site elevation	Sea level (p_{amb} = 29.92 in Hga)

The values were selected as follows:

<u>Steam flow</u>:

As derived from Figure 1, the design steam flow for a number of modern plants plotted against <u>steam turbine</u> output can be reasonably correlated by:

$$\mathbf{W(lb/hr) = 17{,}459 * (MW_{steam})^{0.8132}} \qquad \{3\}$$



3.2.1.1 Figure 1- Correlation of Steam Flow vs. Turbine Output

For a nominal 500 MW, 2 x 1 combined-cycle plant, the steam-side capacity is approximately one-third of the plant total or about 170 MW with a corresponding steam flow of approximately 1.1×10^6 lb/hr.

<u>Steam quality</u>:

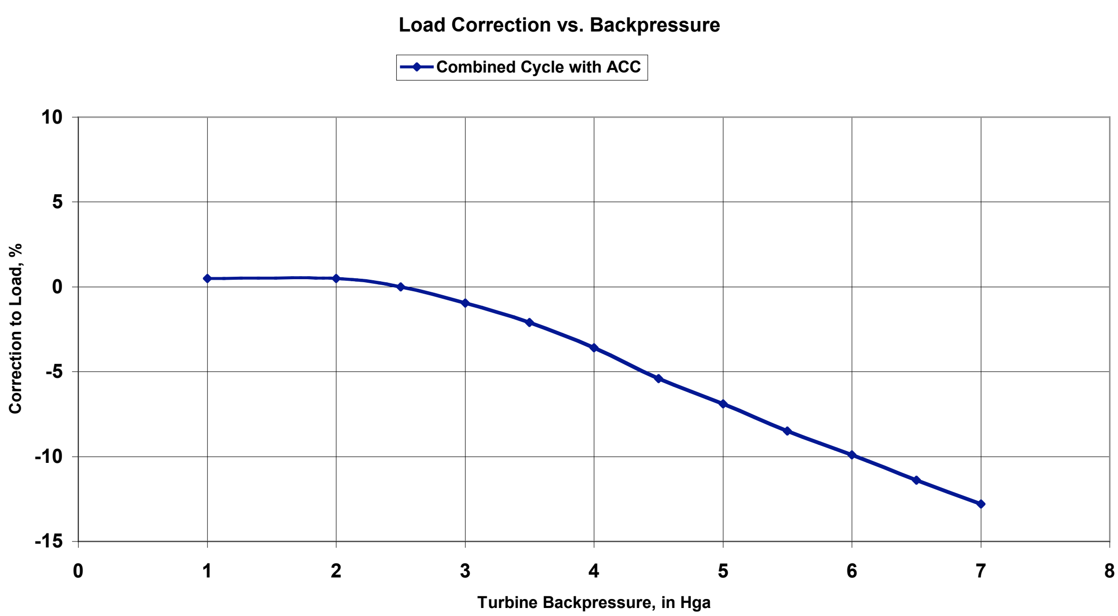
Turbine steam exit quality (or enthalpy) must be obtained from the specific turbine design information or be determined from full-scale turbine tests. Typical values range from 0.92 to 0.98. For estimating purposes, a quality of 0.95 (5% moisture) is a reasonable value. Additional insights are provided in the section on performance testing.

Turbine backpressure and ambient temperature:

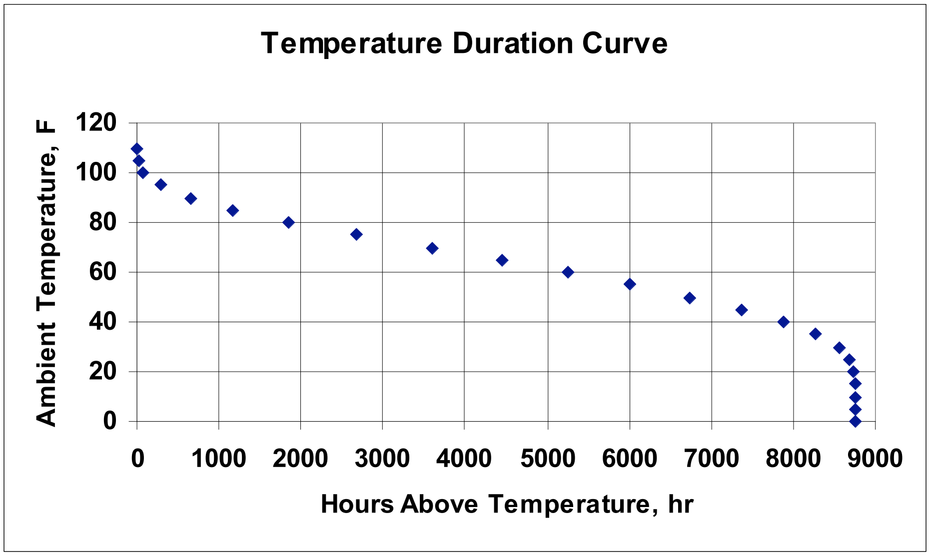
For a given heat load, the combination of turbine backpressure and ambient temperature at the design point essentially determines the size, fan power, cost and off-design performance of the ACC.

Backpressure—Over the normal operating range, the turbine efficiency improves (heat rate decreases) as the backpressure is lowered Figure 2 displays a typical Load Correction vs. Backpressure curve for a turbine selected for use on a combined-cycle plant with an ACC. . Below about 2.0 to 2.5 in Hga, no further reduction in heat rate is achieved and, in some instances, a slight increase occurs. Most turbines are restricted to operating at backpressures below 8. in Hga (typical guidelines are: “alarm” @ 7. in Hga; “trip” @ 8. in Hga).

Ambient temperature---At the desert site chosen for this example, the ambient temperature varies widely during the year. Figure 3 shows a temperature duration curve based on 30-year average data from El Paso, Texas. Other Southwestern sites are comparable.



3.2.1.2 Figure 2 - Steam Turbine Performance vs. Backpressure



3.2.1.3 Figure 3 - Example Temperature Duration Curve

Typical ambient temperature points selected for the design ambient temperature might include the annual average temperature, the summer (June through September) average temperature and the 1% ambient dry bulb (the temperature exceeded only 1% of the year). For this site, these temperatures are:

- Annual average: 65 F
- Summer average: 80 F
- 1% Dry bulb: 99 F

Table 1 lists the Initial Temperature Differences (ITD) for a few combinations of ambient temperatures and condensing pressures.

3.2.1.4 Table 1- ITD Examples for Varying Ambient Temperatures

Initial Temperature Difference (ITD), F				
Condensing Pressure	Condensing Temperature	Ambient Temperature, F		
		65	80	99
in Hga	F	F	F	F
2.5	108.5	43.5	28.5	9.5
3.5	121.1	56.1	41.1	22.1
4.0	126.1	61.1	46.1	27.1
6.0	140.8	75.8	60.8	41.8
8.0	151.8	86.8	71.8	52.8

As can be seen from Table 1, the pairing of a high ambient design temperature with a low design condensing pressure results in a low ITD and, correspondingly, a large and expensive ACC, which would be oversized for most of the year. Conversely, a low design ambient temperature paired with a high design condensing pressure yields a high ITD, a small, inexpensive ACC, but one that would perform poorly during much of the year and severely limit plant output during the hotter periods.

3.2.2 Industry Trends

Over the past twenty years the chosen ITD's for ACC's have gradually decreased and are now typically in the mid-40ºF's or lower. This suggests that the balance of market forces and operating experience over that time have led to the selection of larger units, (having higher capital cost) in order to reduce the performance penalties throughout the year, and particularly during the hotter prevailing ambient conditions. Units with ITD's as low as 50 F were chosen in the early 1980's and as high as 62 F in the late 1990's. Plants whose business strategy and returns depend on selling high priced power during the hottest peak load periods, may well opt for a large unit with a design ITD well below the typical "mid-40's". Further, specification of lower ITD's may reflect greater sensitivity to wind effects on performance and the fact that this is at least one avenue to compensate for these impacts.

4 General Verification of Performance Requirements

General verification of performance of an ACC can generally be conducted by solicitation and evaluation of some of the following information.

4.1 General Requirements Overview

4.1.1 Initial Temperature Difference (ITD)

The ITD will typically be in the range of 25ºF (14ºC) to 60ºF (33.3º). Note that ITD's approaching the low end of this range will result in equipment sizing that may be uneconomical for a specific plant, notwithstanding the obvious benefits to the turbine efficiency. On the other hand, high ITD's, especially in the event of wind-induced performance deficiencies may well result in derating of the power generation unit or a steam turbine trip.

4.1.2 Steam Quality

Steam quality is the weight fraction of steam or percentage of steam at the turbine exhaust. It is typical to have some moisture in the exhaust steam. Typical values of steam quality are 90-95percent, but may be lower depending upon operating conditions of the system. If steam quality were to exceed 100 percent, it would suggest superheated steam still exists at the turbine exhaust. As air-cooled condensers are designed to condense steam and not cool superheated steam, steam quality values at or above 100 percent are not appropriate.

4.1.3 Steam Turbine Exhaust Pressure

Steam turbine exhaust pressure, commonly referred to as "back pressure", will typically be in the range of 2.5 to 7.5 inch Hga. Pressures above this level will typically exceed steam turbine manufacturers' warranties. Accordingly, this high level may be set as a "trip point" (i.e. automatic shut down) for the unit.

4.1.4 Verification of Supplier Performance Requirements of the Air-Cooled Condenser

This section focuses on the Single Row Condenser (SRC) design as it is the most widely offered in response to current air-cooled condenser bid solicitations.

Number of Cells- The number of cells (also referred to as modules) is clearly an important part of the supplier data. Obviously, the number of cells dictates the amount of mechanical equipment (i.e. fans, motors, gear boxes). Further, many current large-scale SRC designs use components, whose dimensions are optimized for shipping and erection. For instance, use of 33 ft (10 meter) diameter fans and individual tube bundle sections of approximately 36 ft (~11m) and with 8 ft (~2.5m)/bundle and 5 bundles per cell per side for a plan area of 36ft by 40ft per cell per side. As a result, the number of cells often dictates a number of features of the air-cooled condenser, including the mechanical equipment as well as the amount of heat transfer surface.

The total number of cells or modules is the sum of the Primary and Secondary Modules. The Primary Modules are responsible for the majority of the heat transfer and condensing, while the Secondary Cells are responsible for residual heat transfer and condensables collection and evacuation.

Number of Primary Modules – The number of Primary Modules is typically about 80 percent of the total number of modules.

Length of Primary Modules - The length of the primary modules is typically on the order of 33ft-40ft (10-13 m) for a Single Row Condenser type system.

Number Of Secondary Modules – The number of Secondary Modules is typically about 20 percent of the total number of modules and there is typically one module per row (or street).

Length of the Secondary Modules – these modules are typically shorter than the primaries by about 3-5 ft (~1 – 1.5 m).

Primary Module Dimensions – (Width) – Obviously the width of the primary modules must be greater than the fan diameter and typically run on the order of 15-25 percent larger than the fan diameter.

Fan Characteristics – Fan diameters for ACC's used on most recent power plant applications are typically 30-37 ft (10-12m). The number of blades per fan will minimally be 5 but may be as many as 8-10 depending upon the fan supplier and the performance requirements.

Motor Characteristics – Fan motor power must be equal to that required by the fan shaft power divided by the motor and gear box efficiencies. Often a margin of 5-10 percent if provided, in addition to service factor margins.

-

4.1.5 Additional Vendor-Supplied Data

A bid specification should also solicit the following information.

Overall Heat Transfer coefficient, **U**, (based on air-side surface area)

b. Total Air-Side Surface Area, **A**
c. Total Mass Flow Rate of Air at Each Design Condition, $\mathbf{m`_{air}}$
d. Fan Static Pressure ($\mathbf{p_{static}}$) or the total system pressure drop.
e. Log Mean Temperature Difference (LMTD)
f. Steam Duct Pressure Drop
g. Heat Exchanger Bundle Pressure Drop (Steam Side)

4.1.6 Important Items for Verification

Thermal Duty – It is important to verify that the thermal duty solicited (i.e. the amount of heat to be rejected) is matched or exceeded by the supplier's offering.

$$Q_{requred\ -} = m`_{steam} \text{ x } (h_{steam,\ (turbine\ exhaust)} - h_{(condensate)}$$

$$Q_{rejected\ =} U \text{ x } A \text{ x } LMTD$$

Heat transfer Area – This is calculated knowing the total heat transfer area of the tubes in the ACC's. For a Single Row Condenser (SRC), the ratio of the air-side surface area and the total "face" area is approximately 124.

Outlet Air Temperature – The outlet air temperature is obviously less than the steam temperature and can be calculated from the following equation:

$$Q_{required} = m` \text{ x } C_{p\ air} \text{ x } (T_{air,\ out} - T_{air,\ in})$$

Face Velocity of the Air - The face velocity of the air, while not typically provided by the supplier, can be calculated from the mass of air flow rate, the air density, and the total face area of the ACC. Typical values will run from about 3 ft/sec (~1m/s) to as much as 8-10 ft/sec (~3 m/s) with the average being about midway between those limits. (Those who have performed velocity measurements at the exit plane of an ACC know that, while the average velocity may be in those limits, variations of a factor of 5 can occur at the outlet).

Fan Static Pressure - Fan Static Pressures will vary depending upon whether the fan is a low-noise or more standard design. Fan Static Pressure, which in essence is the force required to overcome the system resistance (with the required design air flow rate), will run on the order of 0.3 – 0.5 inches of water (~100 Pa +/- 20%) for a standard fan and system design.

Fan Shaft Power or Brake Horsepower - Depending upon the fan static efficiency, one can calculate whether the fan system will deliver the appropriate amount of air.

Power Requirements - Total fan power can be calculated using the aforementioned information and assuming nominal gear box efficiencies of ~97% and motor efficiencies ~92-94%.

5 ACC Performance Test Code Development

Having reviewed some of the key items to solicit in a Specification, as well as those items to check in the bid evaluation stage, the "rubber truly meets the road" with a thermal acceptance test of the equipment.

The American Society of Mechanical Engineers (ASME) and the Cooling Technology Institute (CTI) are currently developing Performance Test Codes for Air Cooled Condensers (ACC). In some respects, development of these Codes may solicit additional caveats for its users.

When test codes are employed for both specification and performance testing of equipment, those who reference them have an inherent confidence that the equipment designed, delivered and successfully tested in accordance with the Code should adequately perform in a plant environment. This is typically the case for components such as turbines, pumps, condensers, and even, for the most part, evaporative cooling towers. Having said that, it is recognized that the performance of evaporative cooling towers can deteriorate under certain wind conditions. Indeed, the impacts of and responsibility for plume recirculation on evaporative cooling towers were key issues for the rewriting of ASME's PTC 23 Atmospheric Water Cooling Equipment. **[3,4].** For the ACC Code Committees at ASME and CTI, it would appear that the challenges are greater yet. The key issues are:

- *ACCs, which perform adequately under the limits of Test Code conditions, may not perform adequately, at all, under normal and prevailing site conditions.*
- *The available knowledge base on wind and performance effects is comparatively limited as the population of and operating experience on larger power plant ACC's, at least in the United States, is limited,*
- *The purchase of ACC's, like most other plant equipment, is cost driven and there are typically no incentives for equipment suppliers to build margin into the design and performance of their offerings.*

5.1 Examples of Performance Impacts

Recognized impacts on ACC performance include:

5.1.1 Wind Effects

Prevailing ambient winds can be high (>10-20 mph) at some sites, leading to:

a. **flow separation** at the fan inlet and poor fan performance,
b. **recirculation** of the hot exit air into the air inlet of the ACC, and
c. **mal-distribution** of the air in the plenum and across the heat exchange surfaces. (additional detail can be found in Reference **[2].)**

5.1.2 Local Interferences

The location of the ACC is necessarily closer to heat sources such as service water cooling systems, turbine exhaust piping, etc. than evaporative cooling towers typically are from the Plant. The entrained air from adjacent sources is very likely to be warmer than design or ambient conditions and therefore the performance of the ACC is negatively impacted.

The net affect of these conditions is that an ACC that appears to meet performance guarantees under the limits of a Test Code, may perform poorly under conditions that prevail at the site. Those who specify, design and own/operate ACCs should be aware of this. Example situations follow:

5.1.3 Example 1 - Waste to Energy Plant

The 3 cell ACC at this site serves a small wood waste power plant. Significant recirculation of the exhaust plume, with localized inlet temperatures exceeding 125F, occurred at this site prior to installation of "wings" down both longitudinal sides of the ACC. Further, a wind screen was installed to reduce wind affects and minimize the entrainment of saw dust in the ACC inlet air. The impact on ACC performance, due to recirculation and flow separation was not anticipated and therefore retrofits of the ACC were made. Inlet air spray cooling is also used at this site.

5.1.3.1 Figure 4 - "Wing" Extensions to Reduce Recirculation

5.1.3.2 Figure 5 - Wind Wall Adjacent to ACC

5.1.4 Example 2 - Small Combined-Cycle Plant ACC

As is the case with many sites employing ACCs, this 20Mwe Plant is located in a water short area. The service water cooling system for this site is an adjacent air-cooled heat exchanger, the exhaust from which enters the inlet of the ACC, when the winds are from the northwest. During a site visit to this plant, localized air temperatures from the service water heat exchanger were 90-92F while the prevailing ambient temperatures ranged from 63-67F. The impact of this on the performance of the ACC was not taken into account during the initial system design and inlet air spray cooling is being considered for peak temperature and load conditions.

5.1.5 Example 3 - Combined-Cycle Power Plant

This plant, located in the desert southwest, has prevailing winds that often exceed 15-20 mph. Impacts of plume recirculation and flow separation have been significant, leading, at times, to de-rating of the plant by nearly 10 percent of its capacity. Retrofits on the ACC included wind walls around the ACC finned tubes to reduce recirculation and perpendicular wind screens below the ACC to reduce wind effects on fan and ACC performance. While the equipment may have met its original performance guarantees, the impacts of prevailing winds have resulted in performance shortfalls that were unanticipated in the original specifications and design process.

5.1.6 Example 4 - ESKOM's Matimba Power Station – South Africa

The Matimba Plant consists of six 680MWe coal-fired power plants. The turbine exhaust is condensed via air-cooled condensers, an aerial view of which is shown in the figure below (courtesy of J. Cuchens, Southern Company).

5.1.6.1 Figure 6 - ESKOM's 680Mwe Matimba Power Station

The ACCs at Matimba are positioned adjacent to the turbine hall on the north side of the Plant. Even though efforts have been made to modify the area, the inlet air path between the turbine hall and ACC's is substantially restricted as a result of the Plant buildings. Prevailing winds are from the Northeast.

Goldshagg [5] reported that turbine performance at the Plant was measurably reduced during certain windy periods and that turbine trips had occurred during gusty conditions. This is not to suggest that turbine back pressures often exceed manufacturer's or plant limits, however, the rate of change of back pressure was significant enough, on more than one occasion, to trigger a Unit trip. The plant has now installed a computer screen, which displays instantaneous wind speed and direction and provides operator guidance on conditions which may impact unit operation. Further, the site has initiated a number of evaluations of inlet air cooling via use of localized spray nozzles.

Those who develop specifications as well as Test Code committee members should consider additional guidance, to those that use the code, calling to their attention the fact that ***actual operating performance of ACC's may be substantially lower than that determined by a test conducted under the limitations currently contemplated by the Code.***

5.2 Testing Guidelines

This section excerpts *(in italics)* portions of the test procedures that are planned for incorporation into the EPRI ACC Specification.

5.2.1 Scope

"1.1 Scope

This document details the measured test parameters, instrumentation, test measurements and data reduction procedure required for determination of the thermal capability of a dry, air-cooled steam condenser (ACC). The procedure focuses on contractual acceptance testing of a new unit, but the same procedure may be used for performance testing of an existing unit.

1.2 Basis

As of this writing there is no American test code for air-cooled condensers. Both the Cooling Technology Institute (CTI) and the ASME are currently working on performance test codes for this major plant component. In the absence of a controlling test code, several resources have been used in the preparation of this guideline. These are:

- ***VGB Guideline for Acceptance Test Measurements and Operation Monitoring for Air Cooled Condensers (1997)***
- ***Code of Practice for Acceptance and Operating Tests of Air Cooled Steam Condensers (published by the Association of German Electricity Supply Authorities in 1965)***
- ***ASME PTC 12.2 Steam Surface Condensers***
- ***CTI ATC-105 Acceptance Test Code for Water Cooling Towers (2000)***
- ***ASME PCT-23 Atmospheric Water Cooling Equipment (2003)***

1.3 Test Plan

A test plan is a convenient vehicle for specification of responsible test participants required preparations, measurement locations, test instrumentation, acceptable test conditions, anticipated deviations to the governing test code, required adjustments to plant operations, calculation procedures, and expected test uncertainty. As an example, the measurement of steam flow and the estimation of steam quality will require the use of plant instruments, particularly flow elements. It is vital that such instruments be identified prior to the test so that any necessary calibrations can be performed. In addition, measurement of condensing pressure requires the installation of basket tips *which may be different in number and location than those used by the plant for monitoring purposes. The preparation of a test plan, approved by manufacturer and the ACC purchaser prior to the test, is highly recommended."…………………………*

Again – as excerpted from the EPRI ACC Draft Specification………

5.2.2 Conditions of Test

"2.1 Test Witnesses
For acceptance testing, representatives of the owner and condenser manufacturer shall be given adequate notice prior to the test. The manufacturer shall be given permission, opportunity and adequate notice to inspect the ACC and prepare the ACC for the test. In no case shall any directly involved party be barred from the test site.

2.2 Conditions of the Equipment
At the time of the test, the ACC shall be in good operating condition. Steam duct and condensate piping systems shall be essentially clear and free of foreign materials that may impede the normal flow of steam and condensate.

Mechanical equipment, including fans, gear, motors, pumps, air ejectors, etc., shall be clean and in good working order. Fans shall be rotating in the correct direction, with proper orientation of the leading and trailing edges. Fan blade pitch shall be set to a uniform angle that will yield within ±10% of the specified fan driver input power load as measured at the motor switchgear.

Air in-leakage must be such that the vacuum equipment has 50% excess holding capacity during the test.

ACC air inlet perimeter area and discharge area shall be essentially clear and free from temporary obstructions that may impede normal airflow.

The air side of the ACC fin tube bundles shall be essentially free of foreign material, such as pollen, dust, oil, scale, paper, animal droppings, etc.

Water level in the condensate hotwell tank shall be at the normal operating level.

Representatives of the ACC purchaser and manufacturer shall agree prior to commencement of testing that the cleanliness and condition of the equipment is within the tolerance specified by the manufacturer. Prior establishment of cleanliness and condition criteria is recommended.

h) All emergency drain lines which have the potential for delivering superheated steam to the condenser shall be isolated. A closed valve shall be considered adequate isolation.

5.2.3 Operating Conditions

The test shall be conducted while operating as close to the operation/guarantee point(s) as possible. In any event, the test shall be conducted within the following limitations:

2.3.1 The test dry-bulb temperature shall be the inlet value, measured in accordance with paragraph 3.3 of this test procedure………………….”

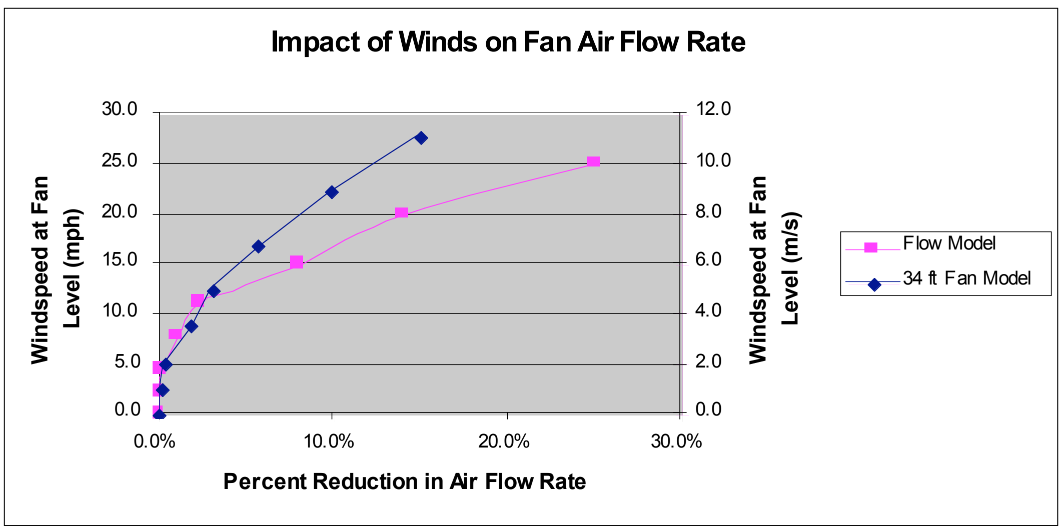
{Note: The following wind limitations are similar to what is being considered by ASME and CTI – however, the performance of the ACC under higher wind conditions will undoubtedly suffer.}

……………..

2.3.2 The wind velocity shall be measured in accordance with Paragraph 3.7 of this test procedure and shall not exceed the following:

Average wind velocity shall be less than or equal to 5 m/s (11 miles per hour).
One minute duration velocity shall be less than 7 m/s (15.6 miles per hour).

Owner/Operators should realize that Air-Cooled Condensers whose performance appears satisfactory under low-wind conditions will fall short of expectations under higher wind conditions. (See Figure 7, below).



5.2.3.1 Figure 7 – Potential Impact of Winds on Fan Performance

It is noted here that Kröger **[1]** suggests the prospect for even greater wind penalties in his example on heat exchanger fan performance.

2.3.3 The following variations from design conditions shall not be exceeded:
<u>*Dry-bulb temperature*</u> - *±10°C from design (18°F) but greater than 5°C (41°F).*

<u>Condensate Mass Flow</u> - ±10% of the design value.
<u>Fan Motor Input Power</u> - ±10% of the design value after air density correction. (Eq. 4-7)

2.3.4 Steam turbine exhaust steam shall be distributed to all modules as recommended by the manufacturer. For the purposes of this Code, a "module" is defined as the smallest subdivision of the ACC, bounded externally by fin tube bundles and internally by partition walls, which can function as an independent unit. Each module generally has a single fan.

2.3.5 There shall be no rain during the test period nor in the one hour period preceding the test period.

2.3.6 Steady state operation of the ACC shall be achieved at least one hour before and maintained during the test.

5.2.4 Constancy of Test Conditions

For a valid test, variations in test conditions shall be within the following limits.

2.4.1 The variation in test parameter shall be computed as the slope of a least squares fit of the time plot of parameter readings. Condensate mass flow shall not vary by more than 2 percent during the tests.

2.4.2 The inlet dry-bulb temperature shall not vary by more than 3°C (6°F).

5.2.5 Duration of the Test

After reaching steady state conditions, the requirements for the test duration shall be at least one hour. Longer test intervals are acceptable provided the constancy of test conditions is observed.

5.2.6 Frequency of Readings

Readings shall be taken at regular intervals and recorded in the units and to the number of significant digits shown in Table 2.0.

Table 3. Measurement Frequency			
Measurement	*Minimum Readings per hour per station*	*Unit*	*Recorded to Nearest*
ACC Condensate Mass Flow [1]	*60*	*kg/h (lb/h)*	*0.1 %*
Condensate Hotwell Tank Level	*60*	*m (ft)*	*0.01 (0.03)*
Exhaust Steam Pressure	*60*	*kPa (in.HgA)*	*0.005 (0.01)*
Exhaust Steam Temperature (for comparison)	*60*	*°C (°F)*	*0.05 (0.1)*
Inlet Air Dry-bulb Temperature	*60*	*°C (°F)*	*0.01 (0.01)*
Atmospheric Pressure	*1*	*kPa (in. Hg)*	*0.2 (0.05)*
Ambient Wind Velocity	*60*	*m/s (mph)*	*0.1 (0.2)*
Fan Power at Switchgear	*1*	*kW (hp)*	*0.5%*

The test procedure in the EPRI ACC Specification document contains data acquisition and analyses procedures as well as options in the Appendices for determination of steam quality. One such option follows, where an attendant steam turbine test is being conducted – as would often be the case when conducted an acceptance test on a new plant.

From Appendices of Test Section……

5.2.7 Procedure for Calculation of Steam Quality at Turbine Exhaust

(*again, excerpted from the draft EPRI ACC Specification)*

The procedure that follows assumes that the slope of the enthalpy versus entropy line for the low pressure steam turbine is independent of the exhaust pressure, inlet temperature, pressure and flow. This is equivalent to assuming a constant isentropic efficiency for the low pressure turbine. Studies using cycle models have indicated that the error involved with calculating the steam quality based on this assumption is less than 1 percent.

1. *From the turbine heat balance diagram corresponding to the air cooled condenser design conditions, obtain the inlet temperature and pressure for the low pressure turbine as well as the turbine exhaust enthalpy and pressure.*
2. *Using steam tables or equivalent software look up (or calculate) the specific enthalpy and specific entropy of the low pressure turbine inlet steam.*
3. *Calculate the quality of the turbine exhaust steam by:*

$$X_d = \frac{h_{e,d} - h_{l,d}}{h_{v,d} - h_{l,d}}$$

where

X_d = *the moisture fraction of the turbine exhaust at the heat balance conditions*

$h_{v,d}$ = *the specific enthalpy of saturated vapor at the exhaust pressure*

$h_{e,d}$ = *the specific enthalpy of the exhaust steam*

$h_{l,d}$ = *the specific enthalpy of saturated liquid at the exhaust pressure*

This value should correspond to the guarantee condition for the condenser.

4. *Calculate the entropy of the turbine exhaust steam by:*

$$s_{e,d} = (1 - X_d)s_{v,d} + X_d s_{l,d}$$

where

s_e = *the specific entropy of turbine exhaust steam*

$s_{v,d}$ = *the specific entropy of saturated vapor at the turbine exhaust pressure*

$s_{l,d}$ = *the specific entropy of saturated liquid at the turbine exhaust pressure*

5. *Calculate the slope of the "expansion line" by:*

$$m_e = \frac{h_{i,d} - h_{e,d}}{s_{i,d} - s_{e,d}}$$

where

m_e = *slope of the expansion line*

$h_{i,d}$ = *enthalpy of the low pressure turbine inlet steam*

$s_{i,d}$ = *entropy of the low pressure inlet steam*

Note 1: The termination point of this expansion line is the Used Energy End Point (UEEP) rather than the expansion line end point (ELEP). The UEEP represents the actual enthalpy of the exhaust steam, while the ELEP is a constructed quantity to allow the calculation of the enthalpy of extraction steam to the low pressure condensate heaters (if any) for which the extraction steam may be saturated.

Note 2: If a turbine test on the unit has been performed, the slope of the expansion line may be calculated by substituting actual values from the turbine test for the design values in steps 1 through 5.

6. *From the temperature and pressure of the turbine inlet steam at test conditions, determine the enthalpy, h_i and entropy, s_i, of the exhaust steam at test conditions.*
7. *Calculate the quality of the steam at the test condition by:*

$$X_T = \frac{(h_i - h_l) + m_e(s_i - s_l)}{(h_v - h_l) + m_e(s_v - s_l)}$$

where

X_T = *the steam quality at the turbine exhaust at test conditions,*

$h_{t,i}$ = *the specific enthalpy of the inlet steam for the low pressure turbine*

s_i = *the specific entropy of the inlet steam for the low pressure turbine*

h_l = *the specific enthalpy of liquid water at the turbine exhaust pressure*

h_v = *the specific enthalpy of vapor at the turbine exhaust pressure*

Se = *the specific entropy of liquid water at the turbine exhaust pressure*

6 Conclusions

The application and popularity of Air-Cooled Condensers (ACC) is increasing in the United States. There are important factors which affect the design, performance, testing and operation of an ACC. Clearly, development of appropriate design information, sensitivity to the impacts of prevailing winds, and guidelines for performance and acceptance testing are key areas of focus.

With this in mind, the Electric Power Research Institute, as part of Project EPP-P10612/C5386, has commissioned the development of a more targeted ACC specification. This paper extracts and presents some key elements of that work in progress.

7 References

[1] Larinoff, M.W., Moles, W.E. and Reichhelm, R., "Design and Specification of Air-Cooled Steam Condensers, *Chemical Engineering,* May 22, 1978.

[2] Kröger, Detlev G., "Air Cooled Heat Exchangers and Cooling Towers", Penwell Corporation, Tulsa, OK, 2004.

[3] Wilber, K. R. and Burns, Jack. '"Examination of the Evolution and Substantiation of ASME's Proposed Test Code on Atmospheric Water-Cooling Equipment", American Society of Mechanical Engineers, Winter Annual Meeting, 1979.

[4] Wilber, K. R. and Maulbetsch, J.S., "Field Examination of Cooling Tower Testing Methodology", Cooling Tower Institute Annual Meeting, January 31-February 2, 1977.

[5] Goldschagg, H.B., "Lessons Learned form the World's Largest Forced Draft Direct Air Cooled Condenser, presented at the EPRI International Symposium on Improved Technology for Fossil Power Plants – New and Retrofit Applications, Washington, March 1993.